Dust formation by the colliding-wind WC5+O9 binary WR 19 at periastron passage*

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ABSTRACT

We present infrared photometry of the episodic dust-making Wolf-Rayet system WR 19 (LS 3), tracking its fading from a third observed dust-formation episode in 2007 and strengthening the view that these episodes are periodic ($P = 10.1 \pm 0.1y$). Radial velocities of the O9 component observed between 2001 and 2008 show RV variations consistent with WC 19 being a spectroscopic binary of high eccentricity ($e = 0.8$), having periastron passage in 2007.14, shortly before the phase of dust formation. In this respect, WR 19 resembles the archetypical episodic dust-making colliding-wind binary system WR 140.

Key words: stars: Wolf-Rayet — binaries: spectroscopic — stars: circumstellar matter — infrared: stars — stars: individual: WR 19.

1 INTRODUCTION

The dense, supersonic winds that give WR stars their characteristic emission-line spectra carry significant mass loss ($\sim 10^{-5}$ M$_\odot$ y^{-1}) and kinetic energy ($\sim 10^4$ L$_\odot$). The release of some of this energy from the collision of such a wind with that of a massive companion in a colliding-wind binary (CWB) system gives rise to a range of theoretically predicted (X-ray emission) and unpredicted (non-thermal radio emission and dust formation) phenomena. The association of dust formation with colliding winds began with the demonstration that the 2900-d periodic dust formation episodes by the archetypal Wolf-Rayet colliding-wind binary WR 140 occurred during periastron passages of its highly eccentric orbit (Williams et al. 1990a). The high densities (10^3– 10^4 times that of the undisturbed Wolf-Rayet wind) required for dust formation to occur can be produced in colliding-wind shocks if they cool efficiently (Usov 1991). The link between the dust-formation episodes and binary orbit in WR 140 is provided by periodic increases of the *pre-shock* wind density by a factor of ~ 40 for a brief time during periastron passage when the separation of the WC7 and O5 stars is at a minimum (Williams 1999). Slightly different behaviour is

shown by the WC7+O9 periodic dust-maker WR 137, whose dust-formation and RV orbital periods are identical within the uncertainties, but there is a 1.3-y (0.1 P) delay between periastron passage and infrared maximum (Williams et al. 2001, Lefèvre et al. 2005). Evidence for a CWB origin for the persistent dust formation by many WC8–9 stars comes from the rotating 'pinwheel nebulae' observed around WR 104 (Tuthill, Monnier & Danchi 1999) and WR 98a (Monnier, Tuthill & Danchi 1999) – although it should be noted that we do not have orbits for these systems, and only WR 104 has a spectroscopic companion.

These results show the way to solving the long-standing mystery of dust formation by Wolf-Rayet stars within the framework of wind compression and cooling in CWBs. The processes are being intensively studied in WR 140, whose orbit is now well defined (Marchenko et al. 2003, Dougherty et al. 2005) and whose dust has been imaged at high resolution (Monnier, Tuthill & Danchi 2002, Williams et al. 2007), but further examples are needed where we can relate the dust formation to the binary orbit.

For this purpose, we selected WR 19 (= LS 3, Smith 1968), which differs from other dust-making WR stars in having an earlier spectral subtype. In her discovery paper, Smith classified its spectrum as WC5+OB, the '+OB' inferred from the weakness of the emission lines (footnote in Smith, Shara & Moffat 1990a, who noted the absence of absorption lines). It was reclassified as a member of the new WC4 sub-class in the Sixth Catalogue (van der Hucht et al.

1981) but was returned to WC5 by Crowther, De Marco & Barlow (1998), in both cases without reference to a companion. In either event, the subtype is earlier than those of the other episodic and persistent dust makers (WC7–8 and WC8–10 respectively). Dust formation by WR 19 was first reported by Williams et al. (1990b, hereafter Paper 1), who found a near-infrared spectral energy distribution (SED) showing 780-K dust emission, which evolved to one characteristic of the stellar wind within two years as the dust emission faded. This prompted continued infrared monitoring to look for another episode of dust formation, and spectroscopy to search for the companion suggested by the weak emission lines (Smith) and possible CWB origin of the dust. The results of both searches were reported by Veen et al. (1998, hereafter Paper 2), who discovered a second dust-formation episode 10.1 y after the first and presented blue-green spectra showing absorption lines from which the companion was classified as a O9.5–9.7 star. They concluded that WR 19 was probably an eccentric WCE+O9.5–9.7 binary.

If the WR 140 paradigm held for WR 19, we expected it to be a spectroscopic binary of fairly high orbital eccentricity having its next periastron passage coinciding with its next dust formation episode in 2007–08. We therefore set out to observe its RV to look for variations to confirm its status as a binary, continuing at least until after 2008. We also sought infrared photometry to confirm the expected dust-formation episode and apparent 10.1-y period inferred from the first two episodes observed. In this paper, we report these observations and the confirmation of the CWB status of WR 19.

2 OBSERVATIONS

The spectra were observed with the EMMI instrument on the 3.5-m New Technology Telescope (NTT) at the European Southern Observatory, La Silla. As the investigation required relatively short observations spread over several years, all but the first were taken in the Service Observing mode, and we continued seeking observations for as long as this programme was offered at La Silla. Fortunately, this continued long enough to take us through periastron passage. We elected to concentrate our search for RV variations on the absorption-line spectrum. We used the EMMI BLMD Grating #3 and set it to give a spectrum running from 3925Å to 4382Å (Fig. 1) covering the interstellar Ca II K line to Hγ. The interstellar lines were included to provide a check on the wavelength scale. An 0.7-arcsec entrance slit gave a spectral resolution of 1.06 Å (2.5 pixels), confirmed from measurement of the interstellar K line. A standard Observing Block (OB) comprising two 1475-s integrations on the star followed by 240 s on the ThAr calibration lamp (separate Th and Ar lamps for the earliest observations) was compiled to fit the 1-h OB limit for service observations. Inevitably, there was a large range in S/N ratio (typically 40–80) in the final spectra depending on the observing conditions, and sometimes two OBs were observed sequentially if conditions were particularly poor.

The spectra were reduced using FIGARO. Initial experiments suggested that the wavelength shifts of the emission features available (Fig. 1) could be determined by cross-correlation with a template derived from a high-quality spec-
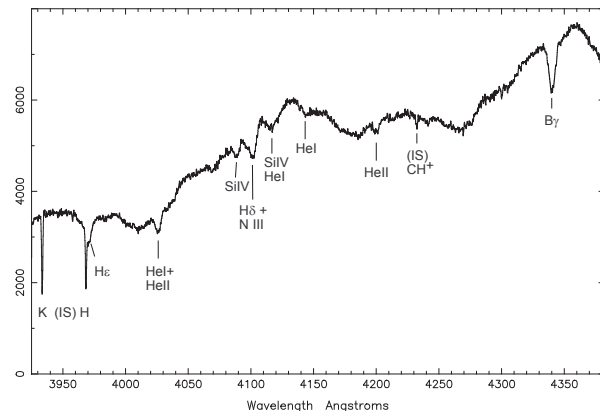

Figure 1. Mean spectrum of WR 19 compiled from spectra observed between 2003 and 2005.

trum (that observed in 2003 January), but this was found not to be the case when more data became available. Instead, we used the cross-correlation method to derive the absorption-line velocities, useful in dealing with blends like that of He II with He I at 4026Å and Hδ with N III at 4097Å and 4103Å, which broadened the profile to 7.3Å compared with 5.7Å for Hγ. The use of a template based on a spectrum of the object star and rectification of the spectral regions covering each of the absorption lines before cross-correlation minimised the introduction of systematic errors in derivation of the RVs. We measured velocities for the absorption lines individually, from which we derived uncertainties, and separated those of the interstellar Ca II H line from Hε by constructing two versions of the template and appropriate masking. Finally, small adjustments to the velocities were made to fit the shifts of the interstellar Ca II H and K lines and, where possible, CH$^+$ at 4232Å. The relative RVs and their errors are given in Table 1 and plotted against date in Fig. 2. We also measured the heliocentric RV of the 2003 January spectrum used for the template by fitting Gaussians to the absorption lines (apart from the Hδ+N III blend) to be 8.6±5.4 km s^{-1}.

The near-IR photometry (Table 2) was derived from images observed with the SofI instrument on the NTT in the large-field (4.9 arcmin) configuration. To avoid saturating the detector, we observed WR 19 through the narrow-band ($\Delta\lambda = 0.03\mu$m) 2.28-μm filter. Each observation comprised an 11-point autojitter each of 3×1.5-s snapshots. The median of these images was used to flat-field the frames. Four stars in the field with high-quality $2MASS$ (Skrutskie et al. 1990) data bracketing WR 19 in K_s and having a range of ($H - K_s$) were used to calibrate the images. The central wavelength of the K_s filter (2.16μm) is shorter than that of the [2.28] filter, and we used the observations of the calibrators to derived a colour equation:

$$[2.28] = K_s - 0.25(H - K_s).$$

From this, we derived the [2.28] magnitudes of the calibrators, and then of WR 19. The latter are given in Table 2 and plotted in Fig. 2. The colour equation does not apply to the magnitudes of WR 19 itself owing to the significant contribution to the K- and K_s-band fluxes of WC stars from the

Table 1. Absorption-line radial velocities (km s^{-1}) of WR 19 relative to that on MJD 52666 (2003 January 26). The phases were calculated using P = 3689 d. from the photometry and T_0 = MJD 50500 from the orbital solution.

MJD	ϕ	RV	s.d.	(O-C)
52079	0.43	-2.8	9.9	-1.3
52666	0.59	0.0	0.0	2.0
53000	0.68	-2.6	9.1	0.3
53002	0.68	-0.9	8.2	2.0
53100	0.70	-1.0	10.0	1.9
53380	0.78	-11.8	7.9	-7.7
53389	0.78	-9.5	10.5	-5.0
53417	0.79	5.0	15.9	9.5
53726	0.87	-3.2	9.8	4.5
53749	0.88	-6.4	8.4	1.6
54089	0.97	-22.7	13.3	5.2
54113	0.98	-45.0	9.4	-10.8
54159	0.99	-38.5	10.6	8.9
54200	1.00	-55.2	8.1	-4.5
54222	1.01	-42.4	13.7	1.4
54225	1.01	-34.7	15.1	7.7
54427	1.06	-14.9	11.5	-4.2
54464	1.07	-15.5	11.4	-6.1
54481	1.08	-13.0	7.0	-4.2
54524	1.09	-7.8	5.3	-0.3
54525	1.09	-0.3	4.9	7.2
54547	1.10	-13.9	7.5	-6.8

Table 2. Narrow-band [2.28] magnitudes of WR 19. The phases were calculated using P = 3689 d. and T_0 = MJD 50500.

MJD	ϕ	[2.28]
54427	1.06	7.61
54463	1.07	7.81
54464	1.07	7.76
54487	1.08	7.87
54511	1.09	7.94
54544	1.10	8.05
54547	1.10	8.00
54557	1.10	8.05

strong emission lines in their spectra (e.g. Williams 1982) and we consider this below.

3 RESULTS

The RVs and [2.28] mags are plotted on the same time-scale in Fig. 2. The velocities show little variation until 2007, when they go through a minimum characteristic of periastron passage in a binary orbit. While the velocities were recovering, the photometry shows rapid fading. We do not have photometry during the RV sequence prior to November 2007, but the photometry in Papers 1 and 2 show an average K = 8.55, much fainter than any of our [2.28] mags, so these results confirm our expectation that WR 19 is a CWB with dust-formation coinciding with periastron passage.

The [2.28] magnitudes are a good measure of the stellar continuum but K magnitudes observed at the same time would have been brighter owing to the contribution from strong emission lines in the broader K filter passband.
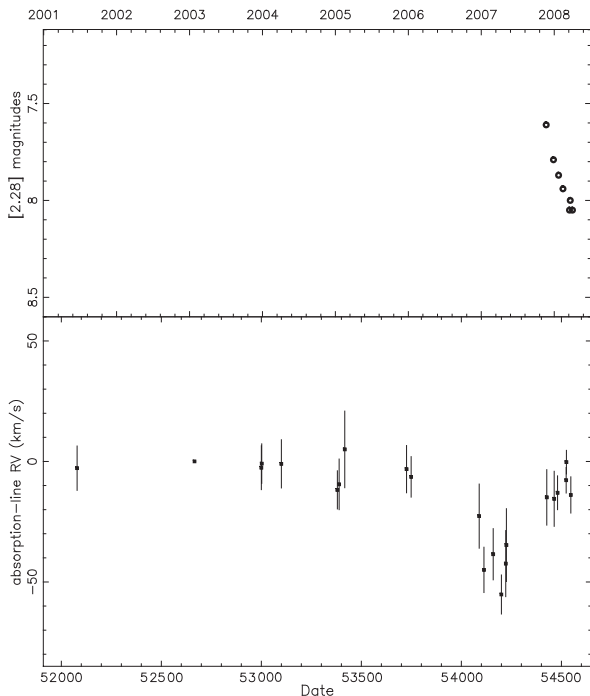

Figure 2. Infrared [2.28] magnitudes (top) and radial velocities (bottom) of WR 19 plotted against date (civil and MJD). The velocities are relative to that in 2003 January. The IR flux is observed to be fading as the system moves away from periastron. The pre-outburst flux level is expected to be [2.28]$\simeq$8.84.
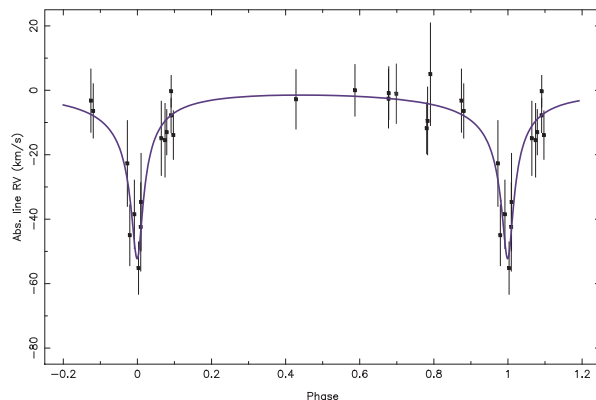

Figure 3. Absorption-line radial velocities and orbit solution plotted against phase.

From low-resolution infrared spectroscopy of WR 19, Smith & Hummer (1988) derived an emission-line correction of $\Delta K = 0.29$ mag. Their spectrum was observed in 1982 May, when the dust emission would have been negligible according to our light curve, so the dust-free WR 19 should have [2.28] $\simeq$ 8.84. Also, we can use Smith & Hummer's measured equivalent widths (totalling 0.13μm in the K passband) to estimate the K magnitudes corresponding to our [2.28] observations, assuming the emission-line fluxes to be constant. The emission-line corrections in 2007–08 are smaller than that in 1982 determined by Smith & Hummer owing to the additional contribution of the dust emission at this time, and range from 0.10 to 0.15 mag. as [2.28] faded from 7.61 to

Table 3. Orbital elements for the O9 component of WR 19 from RVs with period fixed to the photometric period.

Parameter	Value
P	3689 d. (fixed)
T_0	MJD 50500±14
e	0.80±0.04
ω	184°±4°
K	25±2 km s^{-1}
γ	2±5 km s^{-1}
$a\sin(i)$	5.3±0.6 au
f(m)	1.3±0.8 M$_\odot$
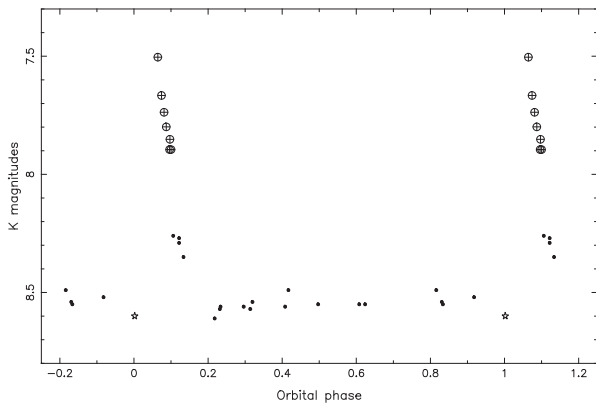
Figure 4. Light curve of WR 19 with K magnitudes from Papers 1 and 2 (●), converted from [2.28] (⊕), and from the DENIS survey (⋆).

8.05, giving 'corrected' K fading from 7.51 to 7.90 in 2007–08. Unfortunately, there is no overlap between these and the K magnitudes observed after the 1988 and 1998 episodes, so we cannot use the new observations to refine the period, but phased light curves using different trial periods and extrapolating the 2007–08 fading showed the new photometry to be consistent with a period equal to the interval of 10.1±0.1 y between the 1988 and 1998 events (Paper 2). This confirms the periodicity of the dust-formation episodes, and observations of the dust-formation episode expected in 2017 would be valuable to reduce the 0.1-y uncertainty.

We then solved the radial velocity orbit with the period fixed to the photometric period, and derived the elements in Table 3. A nominal error of 8 km s^{-1} was attached to the template velocity to avoid over-weighting this point in the RV solution. The RV curve is plotted over the individual velocities in Fig. 3 and the differences from the orbit (O-C) tabulated with the observations in Table 1. Certainly, it would be desirable to have a longer run of RV measurements covering two periastron passages to measure an RV period and test its agreement with that of the photometry, but the present result indicates a high eccentricity orbit with dust-formation at periastron passage. The γ-velocity in Table 3 has been converted to a heliocentric velocity using that of the template (MJD 52666) spectrum.

The K-band photometry, including K converted from [2.28], is plotted against orbital phase in Fig. 4. The converted K magnitudes in 2007–08 show WR 19 to be brighter in the near-IR than any of the previous K photometry (Pa-

pers 1 and 2), indicating that we observed WR 19 closer to its infrared maximum than before, but we still need to observe the maximum and the rise to it, next due in 2017. The rate at which K faded, 1.2 mag y^{-1}, is slightly less that of WR 140 in its early stages, 1.4 mag y^{-1}, and suggests a slightly slower movement of dust away from the stars heating it. The terminal wind velocity of WR 19 needs to be measured to examine this further; radiation pressure from the stars also plays a role by accelerating the dust relative to the wind until it reaches a constant drift velocity and this effect may be smaller in WR 19 than that in WR 140 owing to the later spectral type of the O companion.

Fortuitously, the field including WR 19 in the DENIS survey (Epchtein et al. 1999) was observed almost exactly at the time of the 1997 periastron passage (MJD 50506, $\phi = 0.996$). This observation ($K = 8.58$, close to the mean dust-free level of $K = 8.55$) shows no evidence for dust emission. On the other hand, the first [2.28] observation shows that dust emission was already fading at phase 0.06, i.e. that the dust was cooling as the stellar wind carried it away from the stars heating it, and it was no longer being replenished by nucleation of fresh dust. This constrains the interval during which dust was nucleating to 0.06 P (220 d) at most, with a similar upper limit on the delay between periastron passage and K-flux maximum. This time-scale is comparable to, or slightly slower than, that of WR 140 (0.03 P delay, Williams 1999), consistent with its slightly lower orbital eccentricity ($e = 0.8$, compared with $e = 0.88$ for WR 140, Marchenko et al. 2003), and the idea that dust formation is triggered when the separation of the binary components in their orbit falls below a critical value, leading to a change in the wind-collision process.

We also combined the spectra observed in 2003–05 to form a higher S/N spectrum (Fig. 1) than that used in Paper 2 to re-examine the spectral type of the companion. The wavelength range does not include the 'formal' O-star classification lines, but we compared the relative strengths of the λ 4200Å He II line and visible He I lines with those in Walborn & Fitzpatrick's (1990) atlas and consider the spectral type of the companion to be earlier than O9.5 and closer to O9, which we adopt.

The derived mass function allows us to estimate a minimum mass for the WC star, 11±2 M$_\odot$ assuming 20 M$_\odot$ for the O9 star. This is consistent with the range of masses of WC stars found from binary orbits (9–16 M$_\odot$, van der Hucht 2001). It also suggests that the orbit of WR 19 may be fairly highly inclined unless the mass of the WC star is unusually high.

4   DISCUSSION

The new observations of WR 19 have confirmed its status as a periodic, dust-forming CWB. More observations are needed to strengthen the period and orbit, including the WC star to get a mass ratio, but WR 19 is available as a laboratory to study wind collision effects. For example, spectroscopy of the He I λ1.083-μm line will be valuable not only to determine the wind velocity but also for mapping the wind-collision region through variation of the absorption component and the appearance and movement of sub-peaks

Table 4. Properties of WR 19. including photometry of the dust-free wind.

Parameter	Value	Reference
Spectrum	WC5 + O9	Crowther et al. + this work
Distance	1.7–3.9 kpc	Smith, Shara & Moffat (1990b)
A_v (1.1A_V)	5.6	Smith et al. (1990b)
v	13.85	Smith (1968)
J	9.78	Papers 1 & 2
K	8.55	Papers 1 & 2
L'	8.20	Papers 1 & 2
[8.0]	7.20	*GLIMPSE*

on the broad emission component, as in WR 140 (Varricatt, Williams & Ashok 2004).

Leitherer, Chapman & Koribalski (1997) and Chapman et al. (1999) included WR 19 in their surveys of radio emission from southern WR stars but found only upper limits. This does not rule out non-thermal emission from colliding winds, because the longer wavelength (13 and 20 cm) observations, more likely to show non-thermal emission having a negative spectral index, were taken in 1997.15, very close to periastron passage when the wind-collision region would have been most deeply embedded in the stellar winds and the circumstellar free-free extinction greatest – the non-thermal emission from WR 140 is extinguished at this phase. Re-observation of WR 19 at different phases may reveal non-thermal emission when the geometry is more favourable. We can estimate the radio flux density of WR 19's stellar wind by assuming that its spectral index between mid-IR and cm wavelengths is similar to those of the WC5 stars, WR 111 and WR 114, observed at 6 cm and 3.6 cm by Cappa, Goss & van der Hucht (2004) and Bieging, Abbott & Churchwell (1982) respectively. For the mid-IR fluxes of the stellar wind, we use the *GLIMPSE* (Benjamin et al. 2003) observations of WR 19, taken at phase 0.68 (MJD 52997) when the dust emission is assumed to be long since faded; the *GLIMPSE* [3.6] and [4.5] magnitudes are in excellent agreement with our dust-free L, L' and M magnitudes. To scale the radio flux densities of WR 111 and WR 114, we used the GLIMPSE [8.0] magnitudes of the three stars, leading to an estimated flux densiteis of ~ 0.07 mJy at 3.6 and 6 cm for WR 19. These are about one-quarter the 3-σ upper limit reported by Leitherer et al., so observation of the WR 19 stellar wind should be possible in a reasonable integration time, providing a baseline for studying any non-thermal radio emission.

Similarly, although WR 19 was not detected in the *ROSAT* survey of WR stars (Pollock, Haberl & Corcoran 1993), its confirmation as a CWB and knowledge of its orbit justify re-observation of WR 19 at X-ray wavelengths. Selected properties of WR 19 are collected in Table 4.

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